

The Pressure of In Situ Gases Instrument (PIGI) for Autonomous Shipboard Measurement of Dissolved O₂ and N₂ in Surface Ocean Waters

By Robert W. Izett and Philippe D. Tortell

ABSTRACT. We describe an autonomous flow-through system capable of continuous, unattended measurements of oxygen (O₂) and nitrogen (N₂) concentrations in surface seawater. The derived biological O₂ saturation anomaly, $\Delta O_2/N_2$, can be used to estimate mixed-layer net community production (NCP) in place of $\Delta O_2/Ar$ -based estimates obtained via mass spectrometry. Our Pressure of In situ Gases Instrument (PIGI) consists of two parallel flow-through chambers: the first contains a buoyancy-driven debubbler, and the second houses an Aanderaa optode and Pro-Oceanus gas tension device (GTD). Custom-designed software is provided to visualize and record observations in real time and to post-process data. The system has been tested in the laboratory and on more than 15 deployments in various ocean regions. The PIGI has average optode and GTD response times of ~1.1 min and 1.6 min, respectively; it shows good calibrated accuracy based on comparisons with discrete samples; and the derived $\Delta O_2/N_2$ exhibits strong coherence with independent $\Delta O_2/Ar$ measurements from mass spectrometry. We conclude with recommendations for successful field use and potential future modifications to support a range of deployments strategies. Overall, the system can be used as a cost-effective tool for increasing global coverage of NCP estimates from research vessels, volunteer observing ships, and land-based observatories.

BACKGROUND

Marine net community production (NCP; i.e., photosynthesis minus respiration) is a critical ecological variable that constrains the ocean's capacity for biomass production and carbon export via the biological pump. Ocean metabolism is reflected in surface O₂ variability, such that NCP can be estimated from in situ O₂ measurements obtained along ship tracks, at fixed sites, and on autonomous profilers (e.g., Kaiser et al., 2005; Emerson et al., 2008; Yang et al., 2017). However, physical processes, including temperature-dependent solubility changes and bubble injection, also influence O₂ budgets, and these effects can bias NCP estimates.

For this reason, underway ship-based measurements of biological O₂ saturation anomalies ($\Delta O_2/Ar$) have become increasingly common as tracers of mixed-layer NCP, where argon (Ar) is a biologically inert O₂ analog that corrects for physically induced changes in gas saturation states (Craig and Hayward, 1987).

Presently, underway measurements of $\Delta O_2/Ar$ are obtained using ship-based mass spectrometry, and this technique has yielded many important data sets. Yet, these instruments may be cost-prohibitive for some researchers and require significant power and operator oversight, making mass spectrometry poorly suited for long-term data

collection without significant support infrastructure. This limits the capacity for truly autonomous NCP derivation from underway platforms and volunteer observing ships (VOS). Recent technological advances in O₂ optodes and gas tension devices (GTDs; Tengberg et al., 2006; Reed et al., 2018) have enabled high-resolution, unattended measurements of seawater O₂ and N₂ (McNeil et al., 2005). Ongoing work by our group has evaluated the potential to estimate NCP from O₂/N₂ ratios (i.e., $\Delta O_2/N_2$) in a manner analogous to $\Delta O_2/Ar$ (manuscripts in preparation). Although the solubility properties of N₂ and O₂ somewhat differ, and N₂ is subject to minor biological influences (e.g., N₂-fixation), $\Delta O_2/N_2$ approximates $\Delta O_2/Ar$ under many conditions. Oxygen and N₂ measurements have been combined to infer gas dynamics (Zhou et al., 2014; Tortell et al., 2015) and NCP from refined O₂ budgets (Emerson et al., 2019), but NCP derivation from underway $\Delta O_2/N_2$ remains largely underexploited. The development of a robust system for continuous O₂/N₂ measurement thus has the potential to significantly expand oceanic NCP estimates.

In this article, we describe a system for autonomous, flow-through O₂/N₂ measurements. We provide an overview of this system, named PIGI (Pressure of In situ Gases Instrument), with validation

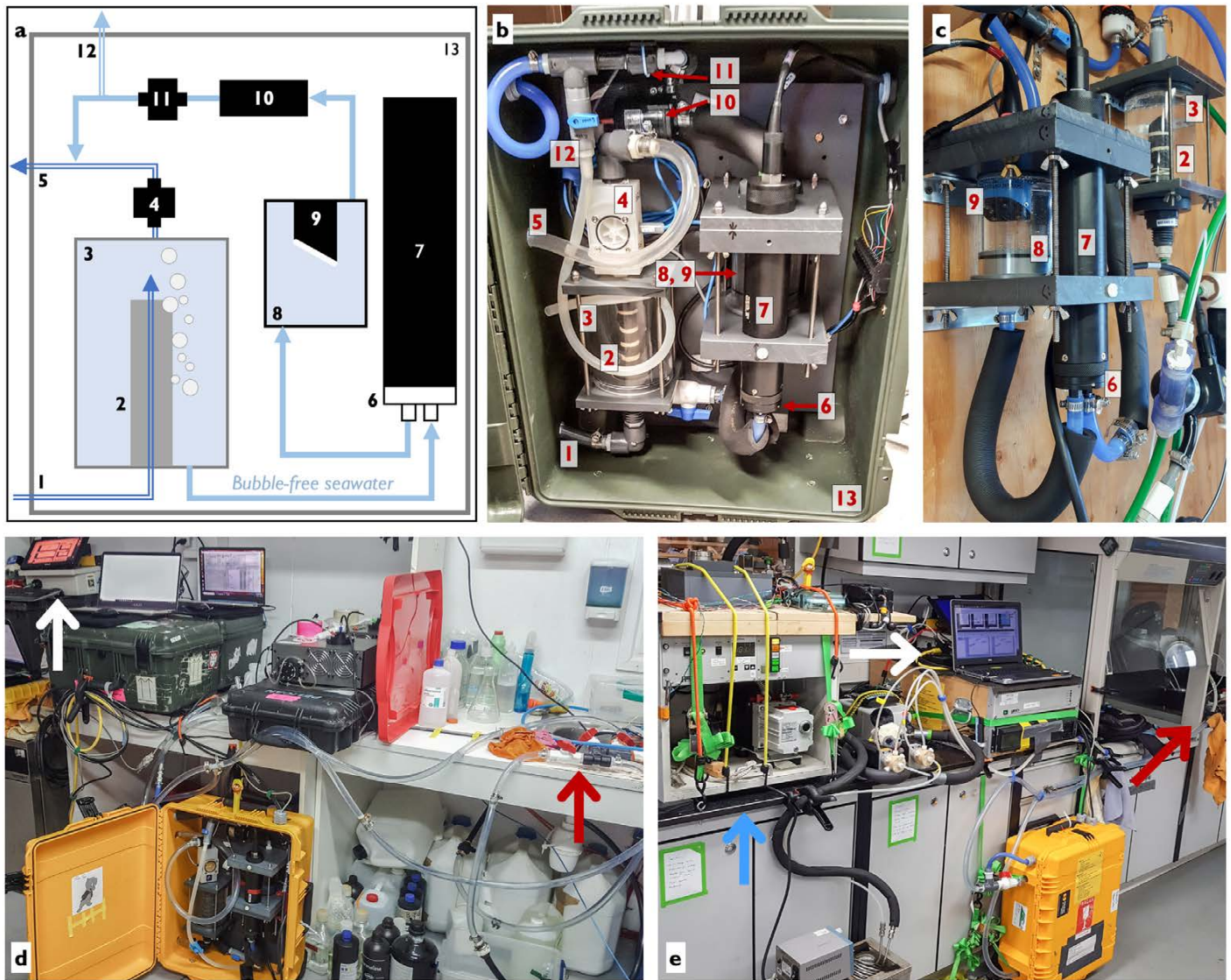


FIGURE 1. A schematic (a) and photographs (b–e) of the flow-through Pressure of In situ Gases Instrument (PIGI) system. Panels (b), (d), and (e) show the system installed in a Pelican case, while (c) shows a wall-mounted version at the Hakai Institute’s Quadra Island Ecological Observatory. Seawater flow paths are represented by blue lines in (a). Labeled parts in (a)–(c) are: system inflow (1), debubbler (2), primary chamber (3), primary chamber flowmeter (4), system outflow (5), TDGP (total dissolved gas pressure)-mini plenum (6), TDGP-mini GTD (gas tension device) (7), optode chamber (8), optode (sensing foil shown in white) (9), centrifugal pump (10), instruments flowmeter (11), discrete sampling line (12), and Pelican case (13). Not all components are shown in (c). PIGI deployments at Base Prat, Antarctica, and on CCGS *Amundsen* are shown in (d) and (e), respectively. The white and red arrows show the locations of the electronics box and the seawater supply. The blue arrow in (e) points to a membrane inlet mass spectrometry (MIMS) system.

results from field deployments and laboratory testing, followed by recommendations for successful field use. Detailed assembly, deployment, and data processing instructions are available in the online supplementary materials.

SYSTEM OVERVIEW

The PIGI is an autonomous measurement system consisting of an electronics box and a flow-through wet box connected to a continuous seawater supply. The wet box (Figure 1) comprises a pri-

mary chamber (~600 mL) containing a custom-built buoyancy-driven debubbler and an instrument loop containing an Aanderaa Data Instruments Optode 4330 (standard sensing foil) and a Pro-Oceanus Systems Inc. mini-TDGP (total dissolved gas pressure) GTD. Seawater entering the system from the ship’s supply first passes through the debubbler to minimize measurement contamination by trapped air. Bubble-free water is then pulled from the primary chamber and past the gas sensors using a centrifugal pump installed

downstream of the instruments.

In the instrument loop, seawater first passes the GTD sensing membrane through a manufacturer-supplied plenum before entering a flow-through cell (~250 mL) containing the optode. Best results (i.e., reduced data noise and optimal instrument response times) are obtained when seawater flows directly onto the sensing faces. Water exiting both chambers merges to form a single outflow line, and check valves are installed to prevent recirculation or drainage of the

centrifugal pump head. Discrete calibration samples can be obtained via a separate line at the outflow of the instrument loop. Flow measurements from both chambers facilitate system monitoring and quality control. Flow rates through the instrument loop should be held constant within 10% of a nominal value, with target rates of $\sim 1.5\text{--}3\text{ L min}^{-1}$ providing optimal data quality.

The wet box components can be mounted directly onto a wall or grating (Figure 1c) or installed on a baseplate secured within a Pelican case (Figure 1b) for protection and easy transport. In either configuration, the system can be disassembled for easy cleaning (see supplemental video) and should be oriented vertically (intake at bottom) so that entrained bubbles escape via the top of the primary chamber (Figure 1a).

The electronics box (Figure S1) runs LabVIEW and AutoIt programs to automate data acquisition and instrument control. AutoIt is used to restart data collection at user-defined intervals.

The LabVIEW program (Figure 2) displays and logs data at a frequency of up to 1 Hz and automatically turns off the instrument's pump to prevent damage during interruptions of seawater flow to the system (e.g., during sea ice blockages). Uncalibrated gas signals (optode O_2 and GTD total dissolved gas pressure), ancillary measurements (temperature and flow rates), and raw sensor signals (e.g., optode phase shift) are saved to a continuously updated ASCII file. Deployment metadata and instrument settings are logged separately at the beginning of each acquisition. The LabVIEW program interfaces with the instruments (e.g., turn pump on/off, set sampling rate), acquires ship GPS information, and performs satellite data transmissions during remote deployments with an optional Iridium transducer module. Data acquisition software and post-processing MATLAB scripts (details in the online supplementary materials) are provided at https://github.com/rizett/PIGI_system.

MATERIALS AND COSTS

The PIGI system can be constructed from readily available materials with relatively basic knowledge of electronic systems. The components of the flow-through chambers are machined from durable PVC and acrylic. Detailed technical drawings and assembly instructions are provided in the online supplementary materials and at <https://seawize.weebly.com/pigi-system.html> (refer to this website for potential future updates). The electronics box contains an Intel Nuc mini-processor, data acquisition board, DC relays, and power supplies. Table 1 summarizes component expenses, and Table S1 provides a comprehensive parts list (including recommended suppliers). Notably, the cost of the optode and GTD sensors (combined $< \$12,000$ US) is significantly less than the cost of a mass spectrometer.

Our system consists of an Aanderaa Optode 4330 and Pro-Oceanus TDGP-mini, but other sensors, such as units Aanderaa designed for shallow water deployments (e.g., models 4531 or 4835; $\sim \$2,700$ and $\$4,775$ US, respectively) or the RBRcoda T.ODO O_2 sensor package ($\sim \$4,500$ US), can be incorporated with only minor adjustments for cost savings. Although users require a LabVIEW license (Table 1) to modify the software we provide, we have also produced a stand-alone version of the data acquisition program that can be used with the free run-time LabVIEW engine (details in the online supplementary materials). Data may also be acquired or processed using alternative open-source software (e.g., Python, Inlino; Haëntjens and Boss, 2020); the online supplementary materials include a description of the workflow required for autonomous operation.

FIELD APPLICATIONS AND LABORATORY AND IN SITU TESTING

Various iterations of the PIGI system have been tested on 19 field deployments since 2016 (Table 2). Our system has been deployed frequently on La Perouse and Line P cruises in the subarctic Northeast

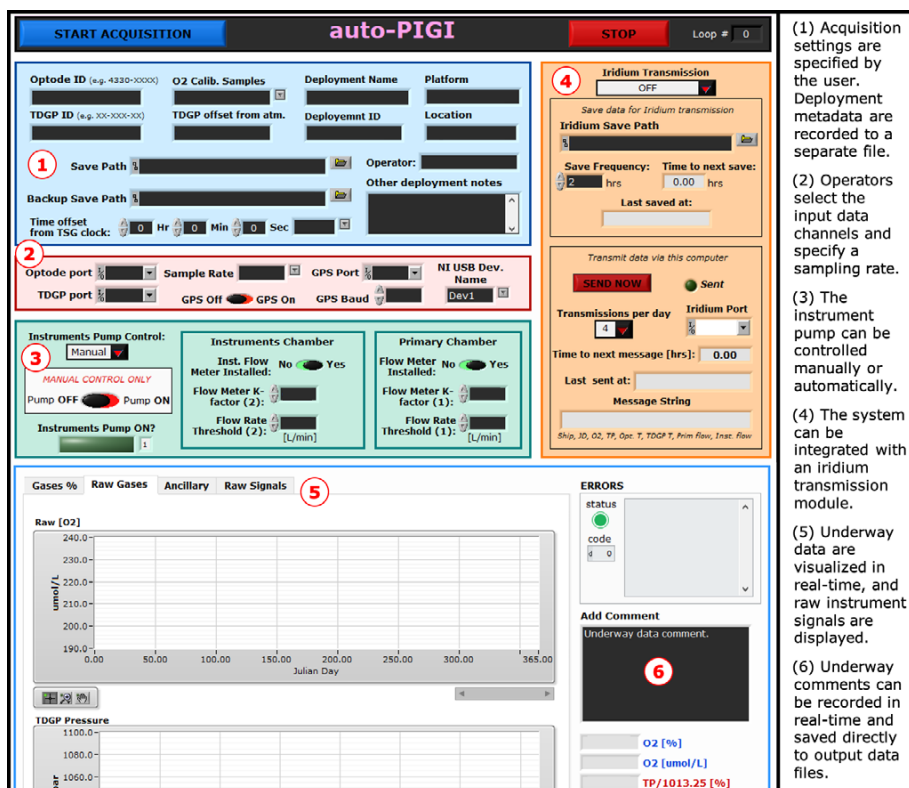


FIGURE 2. A screenshot of the PIGI LabVIEW interface. Data are displayed in real time in the figure panels, and comments corresponding with observations can be recorded to the data file in real time.

Pacific, while a second unit has collected data continuously at the Hakai Institute's Quadra Island Ecological Observatory (in British Columbia's Discovery Islands) for over a year (Figure 1). We have deployed a third system throughout the Canadian Arctic and at a coastal station in Antarctica. A fourth unit will be deployed

on a 2021–2022 R/V *Tara* expedition.

During field deployments, the system was evaluated for underway data accuracy, ease-of-use, and integration with existing instrumentation. Salinity-compensated optode O₂ measurements (see below) were calibrated using discrete samples obtained from the PIGI sampling

line (Figure 1) or surface rosette bottles, and analyzed by Winkler titration. We observed linear relationships between sensor and discrete O₂, with offsets in the uncalibrated data typical of Aanderaa optodes whose accuracy decays over time (Bittig et al., 2018). The strong linearity between sensor and discrete data enables calibration with an average accuracy of 1%, which is required for successful field deployments (Emerson et al., 2019). Optode and GTD-derived N₂ also showed strong coherence with discrete Niskin bottle samples analyzed by mass spectrometry and could be validated to within ~1.2%. The GTD signal shows significantly less drift than optode measurements, so routine calibration with mass spectrometry samples may not be necessary. These results are consistent across multiple deployments and demonstrate that PIGI measurements are not biased by sampling artifacts. Moreover, GTD pressure measurements on air-equilibrated freshwater circulated through the PIGI

TABLE 1. Abbreviated list of expenses of the PIGI system. Full details are provided in the online supplementary materials. Costs are based on quotations obtained in June/July 2020 and exclude local taxes, shipping, and machining expenses. The cost of the wet box includes the gas sensors and additional flow-through parts, while the electronics box expenses include a Windows operating system required to run the automation software, which is quoted separately.

COMPONENT	~ COST (USD)
Calibrated Aanderaa Optode 4330 with cable	\$6,750
Pro-Oceanus mini-TDGP GTD with cable	\$5,000
Wet box total	\$13,500
Electronics box total	\$1,650
System total	\$15,150
LabVIEW Base license (optional)	\$400 (1 yr) / \$3,500 (life)
MATLAB license (optional)	\$860 (1 yr) / \$2,150 (life)

TABLE 2. List of PIGI system deployments between 2016 and present. Cruise IDs are included, where available, in the first column. NCP = net community production.

PROGRAM / CRUISE	SHIP	LOCATION	DURATION (DAYS)	PURPOSE
Line P (2016-001) La Perouse (2016-047) Line P (2016-006) Line P (2016-008) Line P (2017-001) La Perouse (2017-005) Line P (2017-006)	CCGS <i>J.P. Tully</i>	Northeast Pacific/ West Coast Vancouver Island	~100 (total)	testing
2018 ArcticNet Amundsen Expedition (1802 and 1803) ¹	CCGS <i>Amundsen</i>	Labrador Sea, Baffin Bay, Canadian Arctic Archipelago	42 (Jul–Sep 2018)	NCP survey, testing
Line P (2017-008) La Perouse (2017-009) La Perouse (2018-039) Line P (2018-026) Line P (2018-040) Line P (2019-001) Line P (2019-006) La Perouse (2019-023)	CCGS <i>J.P. Tully</i> , CCGS <i>Laurier</i>	Northeast Pacific/ West Coast Vancouver Island	>100 (total)	NCP survey
Hakai Institute coastal monitoring	N/A	Quadra Island Ecological Observatory	Jun 2019–present	NCP time series
2019 ArcticNet Amundsen Expedition (1902) ¹	CCGS <i>Amundsen</i>	Baffin Bay, Canadian Arctic Archipelago	43 (Jul–Aug 2019)	NCP survey
W. Antarctic greenhouse gas survey	N/A	Base Prat, Greenwich Island, Antarctica (Chile)	60 (Jan–Mar 2020)	NCP time series

¹ Data available at https://www.polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=13172

trace atmospheric pressure within $\sim 0.1\%$ across multiple instruments and laboratory tests. We thus conclude that our system is able to accurately determine both O_2 and N_2 concentrations in seawater, provided that necessary calibrations are conducted (see below).

We performed laboratory tests to evaluate PIGI response times by circulating water with contrasting gas compositions (air-equilibrated freshwater and a 1:1 solution of carbonated soda and N_2 -bubbled deionized water) through the primary and instrument chambers at various temperatures and flow rates (Figure 3c). We

determined response times (e-folding time, t_{63}) of O_2 and gas tension signals in the PIGI system ranging from ~ 0.9 min to 1.6 min and 1.0 min to 2.2 min, respectively, based on the time when the water source changed until signals restabilized. These response times are similar to those of a membrane inlet mass spectrometry (MIMS) system used to measure O_2/Ar (Tortell, 2005), and thus permit observations of small-scale oceanic features (Figures 3c and 4). Notably, the instrument response times are shorter at higher temperatures and faster flow rates (lower range of error bars in Figure 3c).

The reported response times reflect the time required to flush the wet box chambers and the water residence time within the optode cell. As a result, the optode response in our PIGI system is longer than the manufacturer's specifications (~ 25 sec) or values reported in different systems (e.g., Bittig et al., 2014). Despite this difference, the GTD signal, with a response time similar to the manufacture specification of 1.5 min, still lags behind O_2 (Figure 4a), so that additional data processing is required when encountering very strong frontal features. Nonetheless, our testing demonstrated that flow rates greater than 1.5 L min^{-1} through the instrument loop (water residence times <1 and <10 sec within the GTD plenum and optode chamber, respectively) produce high-quality data with good spatial resolution. Increasing the seawater flow rates should further improve instrument response times.

Testing also showed that inclusion of a debubbler significantly reduced data noise and contamination from bubbles entrained in ships' seawater lines. Bubble effects are particularly problematic during elevated sea states and, to a lesser extent, in calmer conditions if the seawater intake depth is shallow. Commonly used vortex debubblers increase the water residence time in flow-through systems, thereby leading to excess gas dissolution between the seawater intake and the measurement interface. In the PIGI, we thus designed an upward-oriented debubbler that enables rapid escape of bubbles via buoyant rising (Figure 1). The sampling line leading to the optode and the GTD is installed at the bottom of the debubbling chamber so that bubble-free water is drawn toward the sensors. This approach is very effective in diverting bubbles away from the instruments, even during high sea states. Anomalously high O_2 and N_2 signals can still be measured during elevated sea states, but these result from bubble dissolution in the seawater lines upstream of the PIGI system.

The installation of the pump downstream of the gas sensors and the direc-

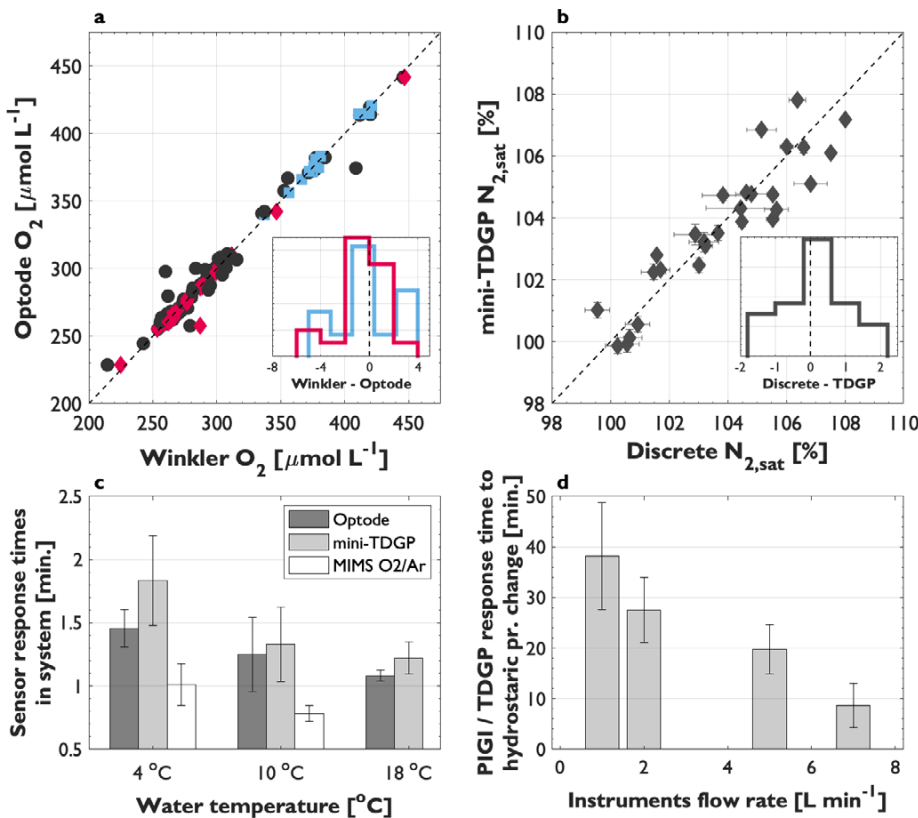


FIGURE 3. Field validation of PIGI-derived O_2 (a) and N_2 (b) against discrete samples. Black markers represent samples obtained from Niskin bottles, and colored markers (blue = Arctic; red = Subarctic Northeast Pacific) are for samples obtained from the PIGI system discrete sampling line. Sensor data have been adjusted for offsets using the discrete samples. The insets in (a) and (b) show the residuals between sensor-derived and discrete gas data, with the y-axis representing the proportion of data points. N_2 saturation ($N_{2,sat}$) represents the seawater concentration normalized to the equilibrium concentration at one standard atmosphere. Panel (c) shows the instrument response times in the PIGI system determined in the laboratory as those required for re-equilibration after a change in the inflowing sample water composition. The response time of a MIMS system, determined under the same conditions, is shown for reference. Error bars represent the range of values recorded during repeat experiments and at different instrument flow rates ($1\text{--}3 \text{ L min}^{-1}$). Panel (d) shows the response time of the mini-TDGP in the PIGI to changes in hydrostatic pressure caused by altering the flow rate through the system. The x-axis corresponds with the flow rate through the instrument chamber during re-equilibration, and error bars represent the standard deviation of values at 4 $^{\circ}$, 10 $^{\circ}$, and 18 $^{\circ}$.

tion of flow onto the instruments' sensing faces (Figure 1) are important for minimizing response times and maintaining neutral hydrostatic pressure within the system. Flow rate changes through the instrument loop following pulses in the discharge from the ship's seawater supply induce hydrostatic effects on GTD measurements analogous to pressure changes during depth profiling (Reed et al., 2018). The PIGI system was designed to minimize these flow-dependent effects and includes flow-rate monitoring for diagnosing such artifacts. Laboratory tests show that GTD response times following such disturbances range between ~10 min and 1 hr, depending on flow rate (Figure 3d). For this reason, it is important to maintain system flow rates as high and as constant as possible.

We also performed side-by-side field deployments of PIGI and MIMS systems (Figure 1e). The results (Figure 4) demonstrate strong coherence between $\Delta O_2/N_2$ and $\Delta O_2/Ar$ across small-scale hydrographic frontal features in Canadian Arctic waters. Offsets between the NCP tracers result from the relatively slow GTD signal and from the slightly different solubility properties of N_2 and Ar . These offsets can be minimized, however, through simple time-response corrections on underway signals (e.g., Bittig et al., 2014; Hamme et al., 2015) and careful evaluation of physical contributions to excess N_2 saturation (manuscript in preparation; Tortell et al., 2015). These results show significant promise for the widespread application of PIGI systems to increase spatial coverage of NCP estimates.

RECOMMENDATIONS AND FUTURE MODIFICATIONS

Throughout system development and testing, we made modifications to PIGI hardware and software to improve overall performance and ease of deployment. Based on our field and laboratory testing of previous versions of the system, we find that the present configuration maximizes data quality. Importantly, the PIGI

was designed for unattended use by operators with little or no previous experience with the relevant instruments. We suggest that future deployments of optode/GTD systems follow similar principles to those discussed here, while considering several recommendations for additional improvements.

Accurate quantification of NCP from O_2/N_2 measurement systems requires ancillary temperature and salinity (T/S) data sets and O_2 calibrations to achieve a desired accuracy of 1%. The latter can be achieved through Winkler analyses on discrete seawater samples or in-air measurements following the approach used on biogeochemical Argo floats (Bittig and Körtzinger, 2015). Nitrogen derivation relies on accurate O_2 and GTD pressure observations, which can be calibrated from in-air measurements made prior to and following deployments. Future PIGI

designs may incorporate an air-pumping system (Bushinsky and Emerson, 2013), so that air-based calibrations could be performed during deployments.

Moreover, T/S data are necessary for performing post-processing calculations on PIGI measurements, including O_2 salinity compensation and the determination of gas partial pressures (details in the online supplementary materials). While optodes include a temperature sensor, salinity measurements must be obtained from separate sensors. If T/S measurements are not made elsewhere on the deployment platform, a salinity sensor can be incorporated in the PIGI instrument loop.

Future systems may also benefit from a smaller optode chamber, which would decrease the optode response time (at a given flow rate) by reducing the optode chamber flushing time. We note, how-

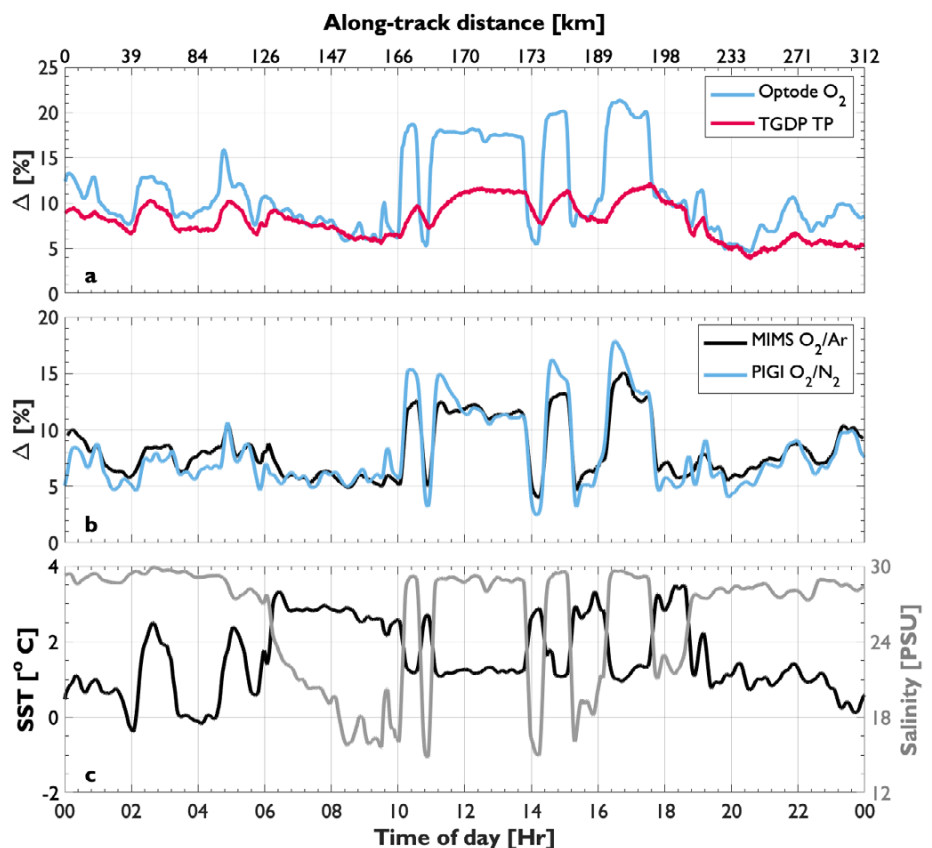



FIGURE 4. One day of field observations from side-by-side deployments of PIGI and MIMS systems near a fjord in the Canadian Arctic. Panel (a) shows the calibrated optode and GTD measurements (normalized to the O_2 equilibrium concentration at ambient sea level pressure and 1013.25 mbar, respectively), with Pro-Oceanus GTD signals seen to lag behind O_2 in strong frontal regions. Derived NCP tracers, $\Delta O_2/N_2$ and $\Delta O_2/Ar$, are presented in (b) and hydrographic data are shown in (c).

ever, that the response time of the GTD in our system remains most limiting to higher resolution $\Delta O_2/N_2$ measurements. In addition, seawater should be pumped rapidly through the primary chamber to reduce overall system response times and minimize the impact of potential bubble dissolution. To limit hydrostatic pressure effects on GTD measurements, a flow controller may be installed in the instrument loop. In its absence, a stable flow rate through the instrument loop should be measured and maintained in order to minimize excursions in the GTD data.

CONCLUSIONS

We describe an automated, user-friendly optode/GTD system capable of high-resolution and accurate O_2/N_2 measurements from a continuous seawater supply. The system has been tested and deployed under a wide range of laboratory and oceanographic conditions and has produced high-quality data from deployments on various platforms. Based on insights from these deployments, we provide recommendations for successful PIGI operation and include detailed designs for the system hardware and software in the online supplementary materials. The system we describe here may be deployed on research vessels and voluntary observing ships or at land-based field stations with a continuous seawater supply. Widespread deployment of the underway PIGI system would lead to a significant expansion of global NCP measurements, providing better understanding of large-scale oceanic responses to ongoing climate variability. 

ONLINE SUPPLEMENTARY MATERIALS

The supplementary materials are available online at <https://doi.org/10.5670/oceanog.2020.214>.

REFERENCES

- Bittig, H.C., and A. Körtzinger. 2015. Tackling oxygen optode drift: Near-surface and in-air oxygen optode measurements on a float provide an accurate in situ reference. *Journal of Atmospheric and Oceanic Technology* 32:1,536–1,543, <https://doi.org/10.1175/JTECH-D-14-00162.1>.
- Bittig, H.C., B. Fiedler, R. Scholz, G. Krahnmann, and A. Körtzinger. 2014. Time response of oxygen optodes on profiling platforms and its dependence on flow speed and temperature. *Limnology and Oceanography: Methods* 12:617–636, <https://doi.org/10.4319/lom.2014.12.617>.
- Bittig, H.C., A. Körtzinger, C. Neill, E. van Ooijen, J.N. Plant, J. Hahn, K.S. Johnson, B. Yang, and S.R. Emerson. 2018. Oxygen optode sensors: Principle, characterization, calibration, and application in the ocean. *Frontiers in Marine Science* 4(429):1–25, <https://doi.org/10.3389/fmars.2017.00429>.
- Bushinsky, S.M., and S. Emerson. 2013. A method for in-situ calibration of Aanderaa oxygen sensors on surface moorings. *Marine Chemistry* 155:22–28, <https://doi.org/10.1016/j.marchem.2013.05.001>.
- Craig, H., and T. Hayward. 1987. Oxygen supersaturation in the ocean: Biological versus physical contributions. *Science* 235(4785):199–202, <https://doi.org/10.1126/science.235.4785.199>.
- Emerson, S., C. Stump, and D. Nicholson. 2008. Net biological oxygen production in the ocean: Remote in situ measurements of O_2 and N_2 in surface waters. *Global Biogeochemical Cycles* 22(GB3023):1–13, <https://doi.org/10.1029/2007GB003095>.
- Emerson, S., B. Yang, M. White, and M. Cronin. 2019. Air-sea gas transfer: Determining bubble fluxes with in situ N_2 observations. *Journal of Geophysical Research* 124(4):2,716–2,727, <https://doi.org/10.1029/2018JC014786>.
- Haëntjens, N., and E. Boss. 2020. Inlinino: A modular software data logger for oceanography. *Oceanography* 33(1):80–84, <https://doi.org/10.5670/oceanog.2020.112>.
- Hamme, R.C., J.E. Berry, J.M. Klymak, and K.L. Denman. 2015. In situ O_2 and N_2 measurements detect deep-water renewal dynamics in seasonally-anoxic Saanich Inlet. *Continental Shelf Research* 106:107–117, <https://doi.org/10.1016/j.csr.2015.06.012>.
- Kaiser, J., M.K. Reuer, B. Barnett, and M.L. Bender. 2005. Marine productivity estimates from continuous O_2/Ar ratio measurements by membrane inlet mass spectrometry. *Geophysical Research Letters* 32:L19605, <https://doi.org/10.1029/2005GL023459>.
- McNeil, C., D. Katz, R. Wanninkhof, and B. Johnson. 2005. Continuous shipboard sampling of gas tension, oxygen and nitrogen. *Deep Sea Research Part I* 52(9):1,767–1,785, <https://doi.org/10.1016/j.dsr.2005.04.003>.
- Reed, A., C. McNeil, E. D'Asaro, M. Altabet, A. Bourbonnais, and B. Johnson. 2018. A gas tension device for the mesopelagic zone. *Deep Sea Research Part I* 139:68–78, <https://doi.org/10.1016/j.dsr.2018.07.007>.
- Tengberg, A., J. Hovdenes, H.J. Andersson, O. Brocandel, R. Diaz, D. Hebert, T. Arnerich, C. Huber, A. Körtzinger, A. Khripounoff, and others. 2006. Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. *Limnology and Oceanography: Methods* 4(2):7–17, <https://doi.org/10.4319/lom.2006.4.7>.
- Tortell, P.D. 2005. Dissolved gas measurements in oceanic waters made by membrane inlet mass spectrometry. *Limnology and Oceanography: Methods* 3:24–37, <https://doi.org/10.4319/lom.2005.3.24>.
- Tortell, P.D., H.C. Bittig, A. Körtzinger, E.M. Jones, and M. Hoppema. 2015. Biological and physical controls on N_2 , O_2 , and CO_2 distributions in contrasting Southern Ocean surface waters. *Global Biogeochemical Cycles* 29:994–1,013, <https://doi.org/10.1002/2014GB004975>.
- Yang, B., S.R. Emerson, and S.M. Bushinsky. 2017. Annual net community production in the subtropical Pacific Ocean from in-situ oxygen measurements on profiling floats. *Global Biogeochemical Cycles* 31:728–744, <https://doi.org/10.1002/2016GB005545>.
- Zhou, J., B. Delille, F. Brabant, and J.L. Tison. 2014. Insights into oxygen transport and net community production in sea ice from oxygen, nitrogen and argon concentrations. *Biogeosciences* 11:5,007–5,020, <https://doi.org/10.5194/bg-11-5007-2014>.

ACKNOWLEDGMENTS

We would like to thank C. McNeil (University of Washington); R. McCulloch, J. Unger, and D. Lovrity (University of British Columbia); and M. Barry (Pro-Oceanus) for their input on instrument design, testing, and technical support. We thank R. McCulloch, H. Bittig, and one anonymous reviewer for their valuable feedback, and many additional colleagues at DFO Canada, Amundsen Science, Hakai Institute, and INACH (including M. Robert, D. Yelland, C. Manning, W. Burt, Z. Zheng, J. Shiller, T. Venello, A. Timmerman, M. Ahmed, R. Hamme, A. Bourbonnais, W. Evans, K. Pocock, C. Weekes, M. Galbraith, T. Fraser, and M. Belton) for their assistance during field deployments. Funding was provided by NSERC, MEOPAR, and ArcticNet.

DECLARATION OF INTEREST

We declare that there are no known conflicts of interest associated with this work. We have not received financial support from Aanderaa Data Instruments AS or Pro-Oceanus Systems Inc.

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ARTICLE CITATION

Izett, R.W., and P.D. Tortell. 2020. The Pressure of In Situ Gases Instrument (PIGI) for autonomous shipboard measurement of dissolved O_2 and N_2 in surface ocean waters. *Oceanography* 33(2):156–162, <https://doi.org/10.5670/oceanog.2020.214>.

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